

Solar Sail Propulsion

Technology Readiness Level Database

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The NASA In-Space Propulsion Technology (ISPT) Projects Office has been sponsoring 2 solar sail system design and development hardware demonstration activities over the past 20 months. Able Engineering Company (AEC) of Goleta, CA is leading one team and L'Garde, Inc. of Tustin, CA is leading the other team. Component, subsystem and system fabrication and testing has been completed successfully. The goal of these activities is to advance the technology readiness level (TRL) of solar sail propulsion from 3 towards 6 by 2006. These activities will culminate in the deployment and testing of 20-meter solar sail system ground demonstration hardware in the 30 meter diameter thermal-vacuum chamber at NASA Glenn Plum Brook in 2005. This paper will describe the features of a computer database system that documents the results of the solar sail development activities to-date. Illustrations of the hardware components and systems, test results, analytical models, relevant space environment definition and current TRL assessment, as stored and manipulated within the database are presented. This database could serve as a central repository for all data related to the advancement of solar sail technology sponsored by the ISPT, providing an up-to-date assessment of the TRL of this technology. Current plans are to eventually make the database available to the Solar Sail community through the Space Transportation Information Network (STIN).

I. Introduction

For many years NASA has used the Technology Readiness Level (TRL) as a method of judging the maturity of a particular technology. Higher TRLs are representative of increases in the technology maturity, ranging from initial concept development to flight quality hardware development. TRLs are generally categorized into (Levels 1-2) technology conceptualization and analytical demonstration, (Levels 3-4) laboratory technology demonstration, component and analytical model validation, and (Level 5-6) component, subsystem and system demonstrations in a relevant environment.

As the TRL of Solar Sail technology has progressed, a tremendous amount of test results, computational models and analysis results have been generated. The Solar Sail Propulsion TRL Assessment Database facilitates the organization, storage and access to this vast amount of data. Correlation of the data with the TRL milestones allows the current level of the technology to be evaluated.

The following sections provide a description of the structure of the database files and configurations of the main and supporting spreadsheets. Features of the program are also described including lists of the technology tasks (tests, demonstrations and inspections) performed on the solar sail hardware. Representative image handling capabilities of the program are demonstrated. Data handling and manipulation features are described, including examples of test results reports and model descriptive data. The solar sail relevant environment definition section of the database is described. Finally, the TRL definition and assessment sections are presented, along with future additions to the database.

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II. Database structure

The solar sails TRL database is structured into 3 folders (References, Pictures and Test Data) as illustrated in Figure 1.

The database utilizes Microsoft Office applications (Excel, Power Point Word, and Access) and Adobe Acrobat Reader. The main application is launched from the Solar Sail Environment Test Checklist spreadsheet file. This file is contained in the Solar Sail Technology Development folder. The "References" folder contains copies of all of the presentations and report files generated during the solar sail technology development program. The "Pictures" folder contains copies of the photographs and video files generated to date. The "Models" folder contains information on the computational models being developed in support of solar sail technology development.

Utilizing the hyperlink, automation functions and Visual Basic for Application (VBA) features

of Microsoft Office to integrate applications, the numerous Power Point, Word, Excel, and Adobe Acrobat files are accessible from within a single file, facilitating review of the vast amount of data generated during the on-going technology development. This integration of data will permit a rapid assessment of the TRL of solar sail propulsion.

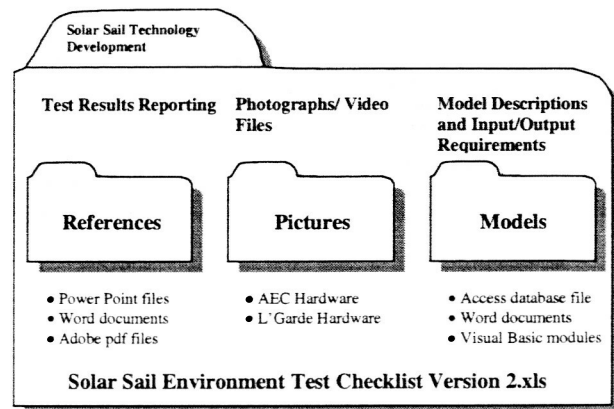


Figure 1. Database File Structure

A. Main Workbook Configuration

The primary platform for viewing and manipulating the database information is the Solar Sail Environment Test Checklist spreadsheet file. This workbook consists of 7 worksheets that correspond with the 3 major near-term products identified in the Solar Sail Technology Assessment Group Roadmap¹. The roadmap is illustrated in the appendix. The "Solar Sail Testing", "L'Garde Hardware Descriptions" and "AEC Hardware Descriptions" worksheets contain information that is a near term product of "Scalable ground test demonstration system" identified on the roadmap. The "Computational Models" and "Model Descriptions" worksheets contain data resulting from the "High fidelity model of test system that demonstrates scalability" roadmap product. The "Relevant Environment" and "References" folders contain information that is a product of the "Set of quantitative laboratory characterization tests".

The "Solar Sail Testing" and "Relevant Environment" worksheets are described in more detail in the following sections. The "L'Garde Hardware Descriptions" and "AEC Hardware Descriptions" worksheets contain photographs of hardware components and systems, as well as computer generated images of systems under development. The "Computational Models" and "Model Descriptions" worksheets contain graphical images of models being developed for solar sails, as well as model descriptive data. The "References" worksheet contains a database table listing of all of the reference files stored in the "References" folder, shown in Figure 1.

The Solar Sail Testing worksheet is illustrated in Figure 2. As highlighted in this figure, technology development tasks are listed in the leftmost column of this worksheet. This list incorporates all of the inspections, demonstrations and tests performed by AEC and L'Garde.

Computational models created as part of the technology development are also listed in the leftmost column. These models are categorized as structural, materials, environment, and guidance, navigation and control (GN&C). A hyperlink is provided to access more detailed model descriptive information.

The Technology Readiness Level definitions are listed in the rows below the computational models section of the worksheet.

AEC and L'Garde hardware components, subsystems and systems names have been entered into the columns across the top of the main worksheet. Command buttons in each of these areas provide access to photographs and video files of hardware items.

Results of the technology tasks performed on each component, subsystem and system are entered in the appropriate intersection of worksheet rows and columns. Comments are entered into each cell to identify the reference document from which the results were obtained.

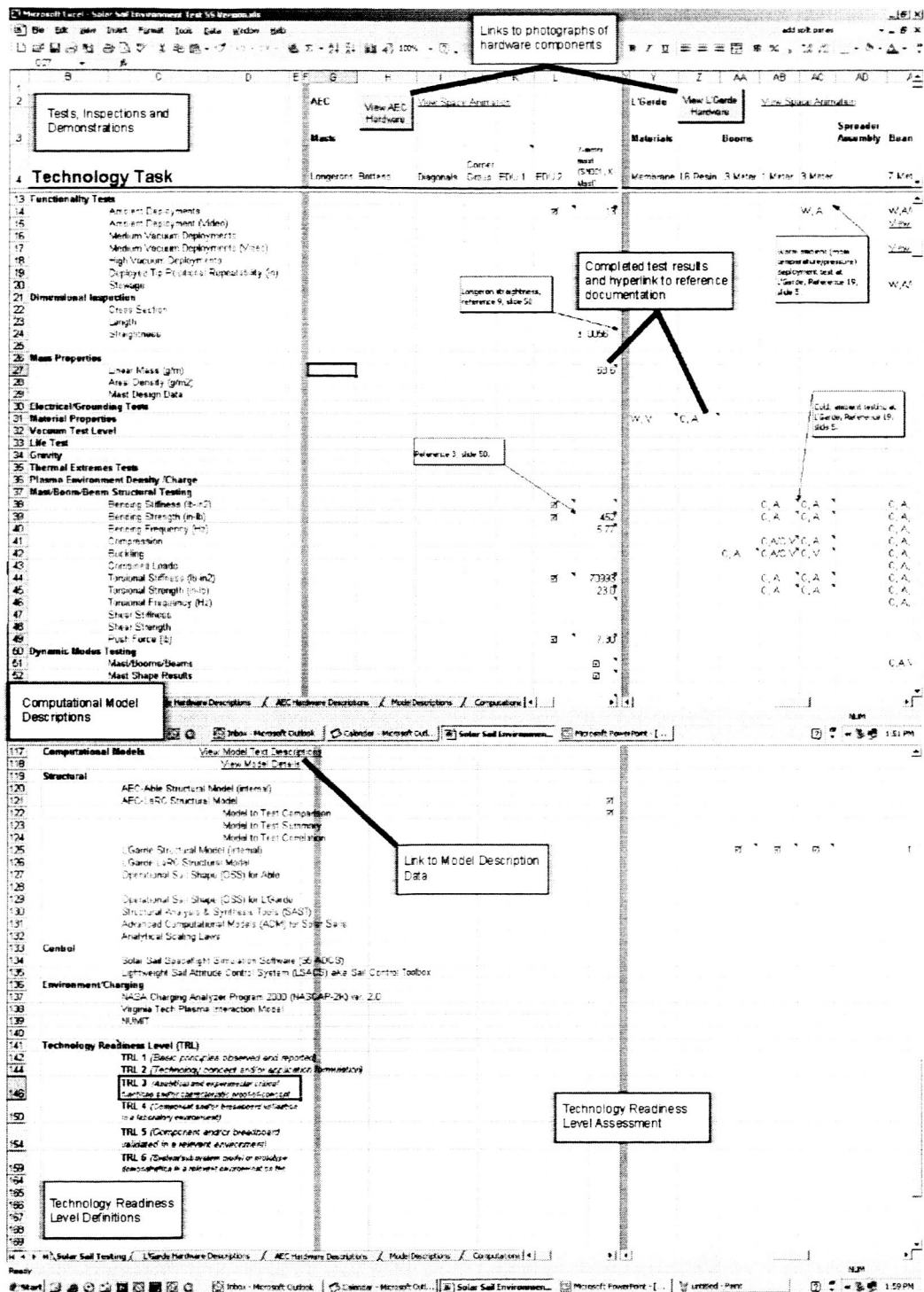


Figure 2. Main Worksheet Configuration

1		
2		
3		
4	Technology Task	
5	Penetration Testing	
6		
7	Material	
8		
9	Cross Section (in)	
10	Modulus (psi)	
11	Bending Strain (+20C) (%)	
12	Bending Strain (+60C) (%)	
13	Fiber Volume Fraction (%)	
14	Functionality Tests	
15	Ambient Deployments	
16	Ambient Deployments (Video)	
17	Medium Vacuum Deployments	
18	High Vacuum Deployments	
19	Deployed Tip Positional Repeatability (in)	
20	Swage	
21	Dimensional Inspection	
22	Cross Section	
23	Length	
24	Straightness	
25	Mass Properties	
26	Linear Mass (g/m)	
27	Areal Density (g/m ²)	
28	Mast Design Data	
29	Electrical/Grounding Tests	
30	Material Properties	
31	Vacuum Test Level	
32	Life Test	
33	Gravity	
34	Thermal Extremes Tests	
35	Plasma Environment Density/Charge	
36	Mast/Boom/Beam Structural Testing	
37	Bending Stiffness (lb-in ²)	
38	Bending Strength (in-lb)	
39	Bending Frequency (Hz)	
40	Compression	
41	Buckling	
42	Combined Loads	
43	Torsional Stiffness (lb-in ²)	
44	Torsional Strength (in-lb)	
45	Torsional Frequency (Hz)	
46	Shear Stiffness	
47	Shear Strength	
48	Push Force (lb)	
49	Dynamic Modes Testing	
50	Mast/Booms/Beams	
51	Mast Shape Results	
52	Swage	
53	System	
54	Sail Shape Measurement	
55	Global	
56	Local	
57	Sail Materials Testing	
58	Mechanical	
59		Construction
60		Thickness
61		Areal Mass
62		Flatness
63		Tensile Modulus
64		Tensile Strength
65		Pd Test
66		Permeation
67		OTF
68		Electrical
69		Resistivity
70		Membrane Tear
71		Resistance
72		Seam Tear
73	Optical	Resistance
74		Absorbency
		Emissivity

1		
2		
3		
4	Technology Task	
5		Reflection
6		Transmission
7		Scatter
8	Space Environmental Effects (SEE) Exposure	
9		Radiation
10		Long term near UV
11		Combined (Fluxure and Radiation)
12		
13	Environmental Degradation Testing	
14		Terrestrial
15		Humidity
16		On-Orbit
17		Environment
18		Electron Radiation
19		Proton Radiation
20		Ultra-Violet
21		Radiation
22		Atomic Oxygen
23		Hydrolytic
24		Impact
25		Vacuum Stability
26		Off-gassing
27		Microstructural
28		Degradation
29		Testing
30		Vacuum Solar
31		Simulation
32	Launch Environment Testing	
33		Acceleration
34		Steady State
35		Dynamic
36		Vibration
37		Acoustic
38		Thermal
39		
40		Post
41		Air and Landing Tests
42		Aerobating
43		
44		Shock
45		Electromagnetic
46		Contamination
47		Ascent Vending
48	System Tests	
49		Plasma Charging Model Testing
50	System Performance Tests	
51		Preparation Test
52	System Performance Analysis	
53		Characteristic Acceleration (mm/sec ²)

Figure 3. Technology Tasks List

Figure 3 provides a more complete list of technology tasks tracked on the “Solar Sail Testing” worksheet. The general categories of technology development tasks include structural, materials, space environmental effects and launch environment. These general categories are further subdivided into dimensional inspections and functionality tests, static and dynamic structural testing, and materials properties measurements (optical, mechanical, thermal). As additional testing requirements are identified, this section of the main worksheet will be expanded to track these test results.

Command buttons provided in the hardware components section of the main worksheet provide the capability to view photographs of the solar sail hardware, as illustrated in Figure 4. AEC solar sail mast components include

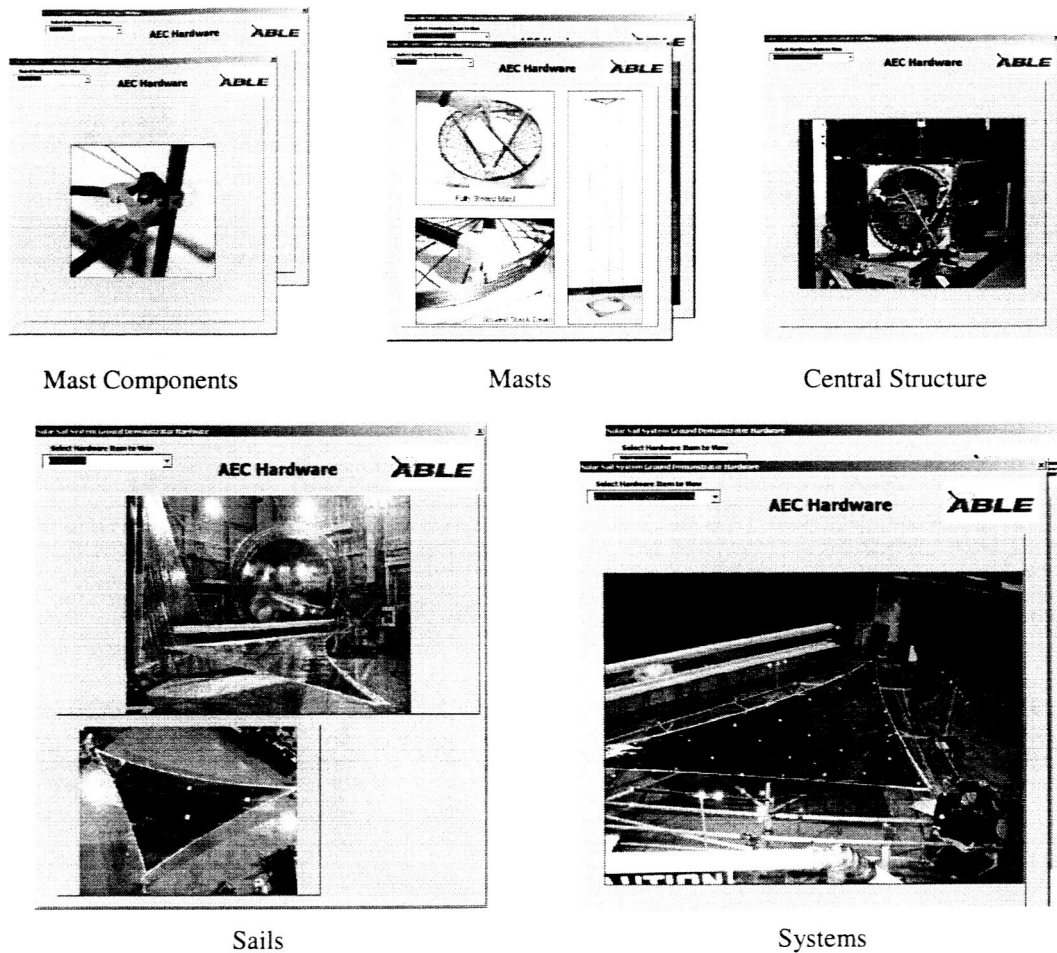


Figure 4. AEC Hardware

longerons, battens, diagonals and corner groups. These components are assembled into mast subsystems. AEC has fabricated several masts to support their technology development activities. Sails developed by the AEC team include the workhorse, RS5, RS3 and the performance sail. The AEC ground support central structure is also shown in this figure. These subsystems are assembled to create the 10 Meter Quadrant and 20 Meter 4 Quadrant Systems.

Future additions to this portion of the database will include details of the AEC thrust vector control authority demonstration hardware and provisions for an optical diagnostics system. This section of the database will be updated to accommodate hardware component advancements as they are developed.

A command button is also provided in the L'Garde hardware section of the main worksheet. This command button provides access to photographs of L'Garde hardware items as illustrated in Figure 5. L'Garde hardware categories include materials (resin, membrane), boom components, beams, central structure, sails and systems. L'Garde has fabricated and tested .3, 1 and 3 meter long booms. The booms and spreaders are assembled together to create a beam. The L'Garde 7 Meter beam is illustrated in the figure. L'Garde has fabricated and assembled sails including the 2/3 sail, a 9 cell rip-stop sail and a 10 Meter quadrant. Photographs of the L'Garde central structure, 10 Meter 4 Quadrant and a concept for the 20 Meter ground system demonstrator are also shown in the figure.

Future additions to this portion of the database will include details of the L'Garde thrust vector control authority demonstration hardware and provisions for an optical diagnostics system. This section of the database will be updated to accommodate hardware component advancements as they are developed.

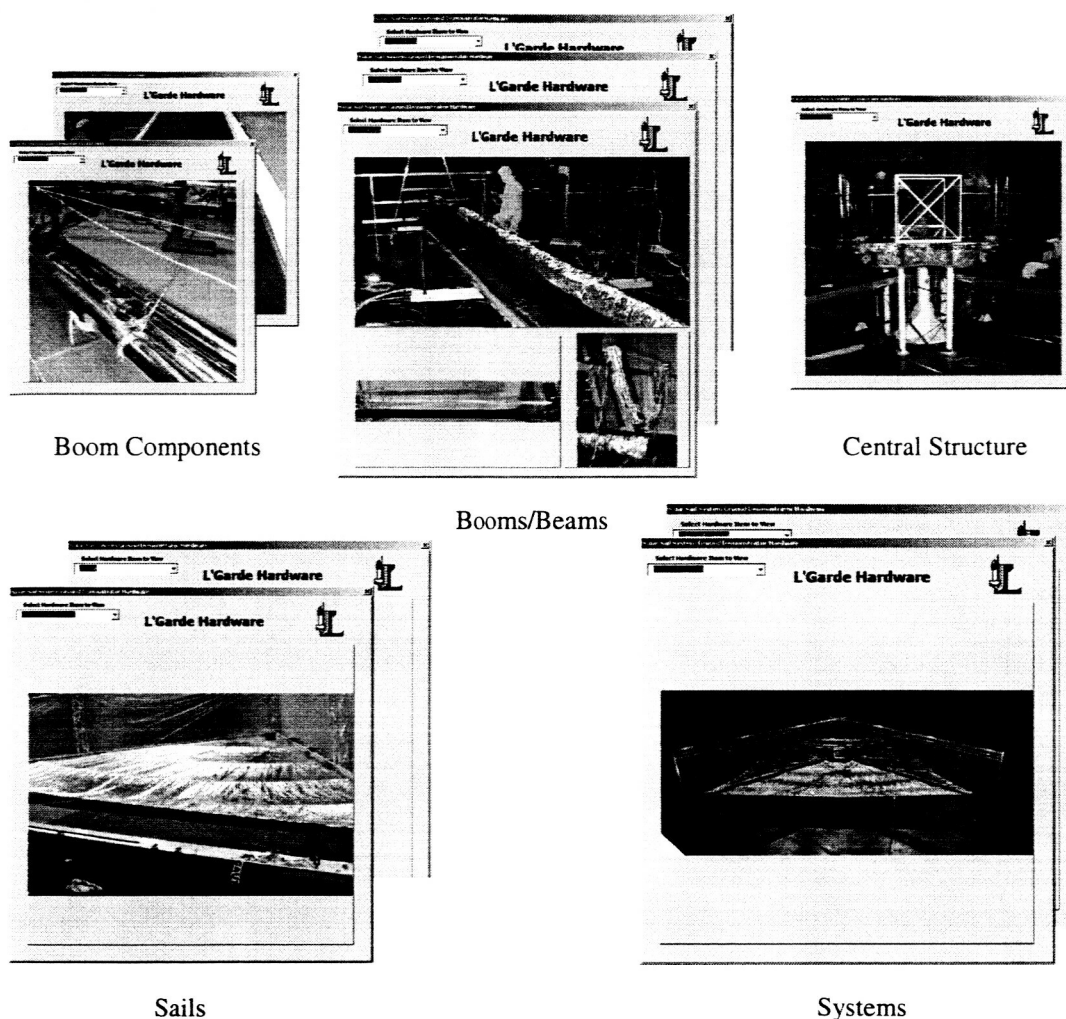


Figure 5. L'Garde Hardware

Hyperlinks are also provided in the main worksheet to view deployment video files and on-orbit deployment animations of both the L'Garde and AEC hardware.

B. Worksheet Row/Column Cell Entries

Results of the tests, analyses, inspections and demonstrations performed to date on the AEC and L'Garde hardware are entered into the spreadsheet in the appropriate column and row intersection. Annotations in the cell comments are entered to link the test results to the specific reference (Power Point slide, Word document, PDF file) where the results of the specific test were documented. By "double clicking" on the specific cell of interest, a VBA

The screenshot displays the 'Sail Verification Matrix' software interface. The window title is 'Sail Verification Matrix'. The interface includes a menu bar (File, Edit, View, Format, Window, Help), a toolbar, and a main data table. The table has columns for 'Material', 'Properties', and 'Results'. The 'Material' column lists various sail components like 'Main', 'Mast', 'Boom', etc. The 'Properties' column lists properties like 'Area', 'Weight', 'Stiffness', etc. The 'Results' column contains numerical data. A legend at the bottom left shows color-coded boxes for 'Pass', 'Fail', and 'Warning'. A list of notes is on the bottom right, including 'MEFC Near UV testing begins Mid Dec' and 'BOL Mechanical and optical properties preliminary results received'. The bottom status bar shows 'FILE EDIT VIEW FORMAT WINDOW HELP' and 'Sail Verification Matrix v1.0.0'.

Material	Properties	Results
Main	Area	1.2
Main	Weight	1.5
Main	Stiffness	1.8
Mast	Area	1.2
Mast	Weight	1.5
Mast	Stiffness	1.8
Boom	Area	1.2
Boom	Weight	1.5
Boom	Stiffness	1.8
...

Legend:

- Pass (Green box)
- Fail (Red box)
- Warning (Yellow box)

Notes:

- MEFC Near UV testing begins Mid Dec
- BOL Mechanical and optical properties preliminary results received

Status Bar: FILE EDIT VIEW FORMAT WINDOW HELP Sail Verification Matrix v1.0.0

[illegible]

L'Garde Results Reporting

C. Solar Sail Computational Models

Model validation is a key element of TRL advancement. Detailed descriptions of the solar sail computational models can be accessed within the database by clicking on the appropriate command button. An example of the computational model descriptive data is illustrated in Figure 7. Model descriptive data displayed includes model name, purpose, owner, implementation strategy, model inputs/outputs, platform, status, pointers, status of validation and space experiment validation. Illustrations of the model graphics can also be accessed by “clicking” on hyperlinks in the “Models” section of the spreadsheet.

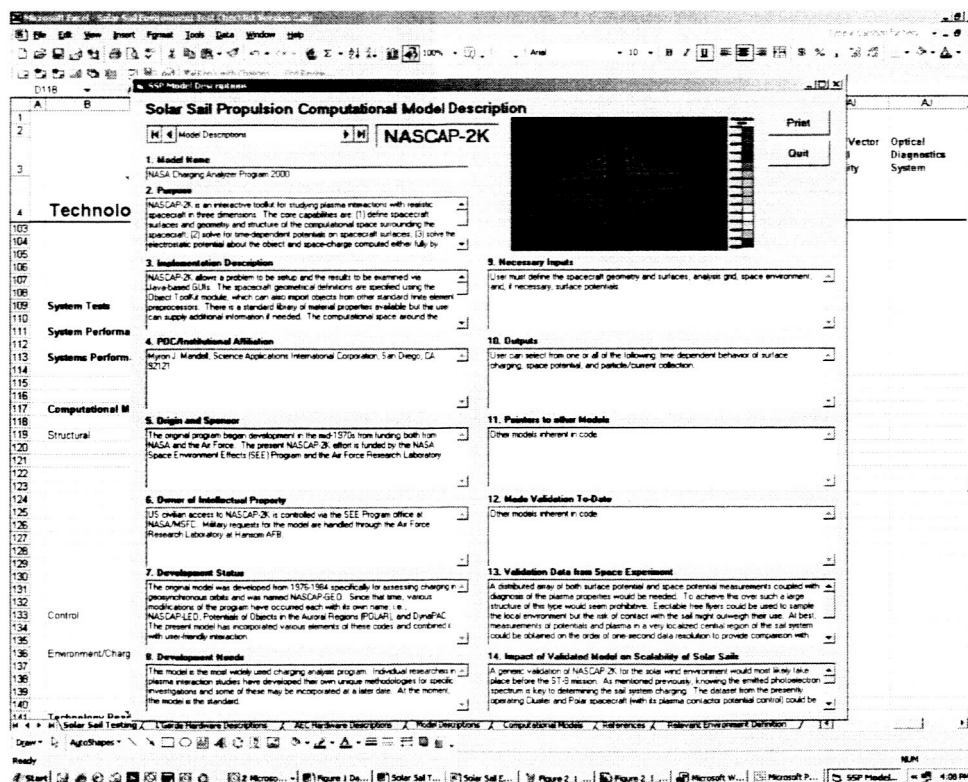


Figure 7. Computational Model Description Interface

D. Relevant Environment Definition

Another key element of advancing the TRL of a technology is defining the "relevant environment" for the technology. Data related to the relevant environment definition for solar sail technology is stored in a separate worksheet in the main workbook. This worksheet is illustrated in Figure 8. Environment conditions included in this worksheet include the launch environment (vibration, thermal, ascent venting). On-orbit environments include the vacuum level and thermal (solar direct heating, solar reflected heating and earth radiated infrared heating). On-orbit micrometeoroid/orbital debris, radiation, and atomic oxygen environments are also designated. The current design reference missions for Solar Sail Propulsion include the L1 Diamond mission and the Solar Polar Imager mission. Orbit parameters for the design reference missions are also stored in this worksheet. Another potential "relevant environment" to be considered is the ST9 Solar Sail Flight Validation (SSFV) Mission. The specific orbit parameters for this mission are still being determined. The most stringent environments for each of the missions will be considered in specifying the test conditions appropriate for relevant environment testing for TRL advancement.

Solar Sail Technology Relevant Environment Definition				Design Reference Mission: (L1 Diamond)				Solar Sail Flight Validation			
Design Unique Values				Orbit Parameters				Orbit Parameters			
AEC L/Garde				Launch date				Launch date			
Temperature (°C)				Perigee (km)				Perigee (km)			
Sail				Apogee (km)				Apogee (km)			
Maximum				Inclination (°) (degrees)				Inclination (°) (degrees)			
Minimum				Ascending Node Local Time (hours min)				Ascending Node Local Time (hours min)			
Missions/Booms				Longitude (geostationary) (degrees east)				Longitude (geostationary) (degrees east)			
Central Structure				Semi-major axis (a) (km)				Semi-major axis (a) (km)			
Other				Eccentricity (e)				Eccentricity (e)			
Pressure (Torr)				Orbit Period (sec)				Orbit Period (sec)			
Gravity (Gs)				Orbit Period (minutes)				Orbit Period (minutes)			
Radiation (rads/hr)				Mean motion (n) (rad/sec)				Mean motion (n) (rad/sec)			
Plasma Charging				Mean motion (km/sec)				Mean motion (km/sec)			
Galactic Cosmic Rays				Circular Orbit Parameters				Circular Orbit Parameters			
Metecoid Flux				Velocity (km/sec)				Velocity (km/sec)			
Atmosphere (Atomic Oxygen)				Earth angular size from satellite (degrees)				Earth angular size from satellite (degrees)			
Thermal Environment				Angle of horizon below horizontal (degrees)				Angle of horizon below horizontal (degrees)			
Solar radiation (albedo and OLR variations)				Perturbations				Perturbations			
Radiative transfer				Node Rate (deg/day)				Node Rate (deg/day)			
Neutral Thermosphere				Perigee Rate (deg/day)				Perigee Rate (deg/day)			
Atmospheric Density				Node Rate per orbit (deg/orbit)				Node Rate per orbit (deg/orbit)			
Density variations				Transfers				Transfers			
Atmospheric composition (Atomic oxygen)				Escape velocity (km/sec)				Escape velocity (km/sec)			
Winds				Sun Information at Launch				Sun Information at Launch			
Plasma				Beta angle (angle from orbit plane) (degrees)				Beta angle (angle from orbit plane) (degrees)			
Ionospheric plasma				Eclipse duration (circular orbit) (minutes)				Eclipse duration (circular orbit) (minutes)			
Auroral plasma				Pass Information at Launch:				Pass Information at Launch:			
Magnetospheric plasma				Ground station longitude (degrees East)				Ground station longitude (degrees East)			
Micrometeoroid and Orbital Debris				Ground station latitude (degrees North)				Ground station latitude (degrees North)			
MFCO flux				Ground station min elevation (degrees)				Ground station min elevation (degrees)			
Size distribution				Maximum nadir angle (degrees)				Maximum nadir angle (degrees)			
Mass distribution				Maximum Earth central angle (degrees)				Maximum Earth central angle (degrees)			
Velocity distribution				Maximum distance (km)				Maximum distance (km)			
Directionality				Gravity Gradient Torque				Gravity Gradient Torque			
Solar Environment				Drag				Drag			
Solar physics and dynamics				Radiation Dose				Radiation Dose			
Geomagnetic storms				Disposal				Disposal			
Solar activity predictions											
Solar geomagnetic indices											
Solar constant											
Solar spectrum											
Ionizing Radiation											
Transfer proton/electron radiation											
Galactic cosmic rays											
Solar particle events											
Magnetic Field											
Natural magnetic field											
Gravitational Field											
Natural gravitational field											
Mesosphere											
Atmospheric Density											
Density variations											
Winds											
Launch Environment											
Acceleration											
Steady State											
Dynamic											
Vibration											
Acoustic											
Thermal											
Pad											
Ascent battery radiant											
Ascent heating											
Shock											
Electromagnetic											
Contamination											
Venting											

Figure 9. Relevant Environment Definition

E. Technology Readiness Level Definitions

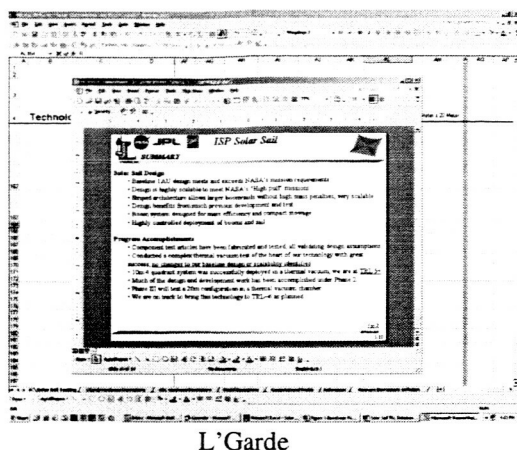
The final section of the main worksheet addresses the TRL assessment of the technology. Descriptions of the requirements for each of the TRL levels are included in this section of the "Solar Sail Testing" worksheet. These definitions will be used to determine when each of the TRL milestones has been reached. Figure 10 illustrates the TRL definitions section of the "Solar Sail Testing" worksheet.

Technology Readiness Level (TRL)	
TRL 1 (Basic principles observed and reported)	1. Basic principals observed and reported.
TRL 2 (Technology concept and/or application formulation)	1. Technology concept and/or application formulated.
TRL 3 (Analytical and experimental critical functions and/or characteristic proof-of-concept achieved in a laboratory environment)	<ol style="list-style-type: none"> 1. Laboratory tests have demonstrated the technology advance as predicted by the analytical model and has the potential to evolve to a practical device. 2. Analytical models both replicate the current performance of the technology advance and predict its performance when operating in a breadboard environment. 3. A determination of the "relevant environment" for the technology advance has been made.
TRL 4 (Component and/or breadboard validation in a laboratory environment)	<ol style="list-style-type: none"> 1. A "component" or "breadboard" version of the technology advance will have been implemented and tested in a laboratory environment. 2. Analytical models of the technology advance fully replicate the TRL 4 test data. 3. Analytical models of the performance of the component or breadboard configuration of the technology advance predict its performance when operated in its "relevant environment" and the environments to which the technology advance would be exposed during qualification testing for an operational mission.
TRL 5 (Component and/or breadboard validated in a relevant environment)	<ol style="list-style-type: none"> 1. The "relevant environment" is fully defined. 2. The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission. 3. Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment".
TRL 6 (System/subsystem model or prototype demonstration in a relevant environment on the ground or in space)	<ol style="list-style-type: none"> 1. The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft. 2. The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission. 3. Analytical models of the function and performance of the system/subsystem model or prototype throughout its operating region, in its most stressful environment, have been validated empirically. 4. The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for

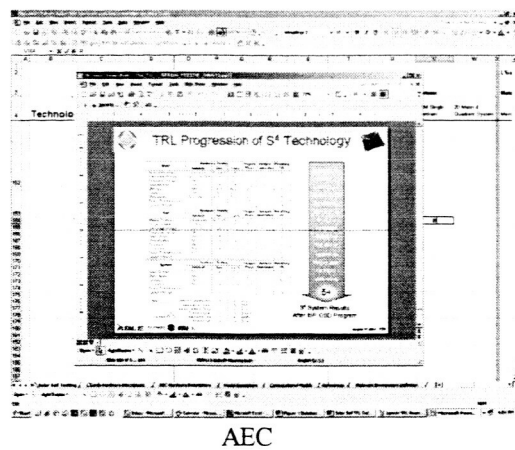
Figure 10. Technology Readiness Level (TRL) Definitions²

F. TRL Assessment

To assess the TRL of the technology, the definition of each TRL is compared with the results of the tests, analyses, and model validation results contained in the rows for each of the hardware items. As the requirements for TRL milestones are satisfied, the TRL for that hardware item is advanced. Individual engineering judgment does play a role in the assessment of technology maturity. However, the Solar Sail TRL Assessment Database will facilitate the comparison of TRL requirements with technology task completion. Current internal TRL assessments made by the L'Garde and AEC teams are illustrated in Figure 10. NASA is in the process of performing a separate TRL assessment of the state of solar sail technology. This assessment will be added to the database when it is completed.



L'Garde



AEC

Figure 10. L'Garde and AEC TRL Assessment

G. Status and Future Database Additions

Testing of 10 meter solar sail systems by both AEC (at the LaRC 16 Meter Diameter Vacuum Chamber) and L'Garde (at the GRC Plum Brook 100 Foot Diameter Vacuum Chamber) has been completed. Results of these tests are being added to the database. 20 meter system testing, including the demonstration of a thrust vector control system, will occur in the spring of 2005. These results will also be added to the TRL database.

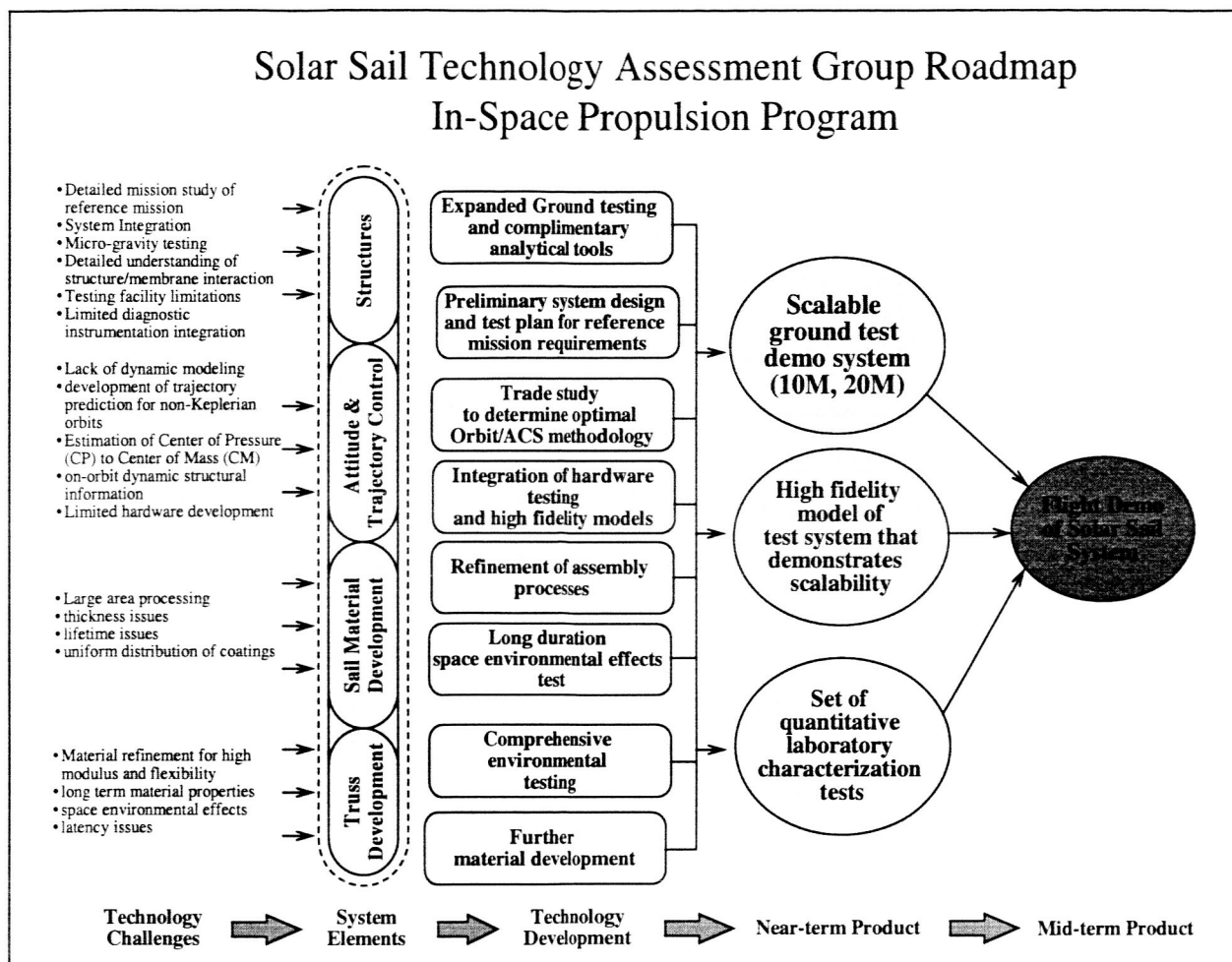
Relevant environment definitions are in progress. Following detailed definition of the proposed ST9 Solar Sail Flight Validation orbit, the launch and on-orbit environments will be defined for the mission. This will allow the complete relevant environment to be defined.

Required model input and output data requirements are being gathered for each of the models under development to support model validation. Correlation of model predictions with the test results will be entered into the computational model section of the spreadsheet as these correlation activities are completed.

H. Summary

A TRL assessment database has been developed for solar sail technology. This database provides centralized access to all of the results of hardware development testing activities, model development and correlation efforts and relevant environment definitions. The database structure can be easily reconfigured or expanded as necessary to accommodate additional data handling requirements. The database is organized to provide centralized storage and access capabilities for all of the technology development results reporting, providing an automated tool for evaluating the TRL of solar sail technology.

Appendix



Acknowledgment

The efforts reported on in this paper are sponsored under the SAIC Integrated Space Technology Assessment prime contract with the Marshall Space Flight Center In-Space Propulsion Technology Projects Office.

References

- ¹"Solar Sails Technology Assessment Group Final Report", G. Garbe, NASA/MSFC, January 29, 2002.
- ² New Millennium Program (NMP), Technology Readiness Levels for the New Millennium Program, May 22, 2003, Version 1.